HUMAN-CENTERED ELECTRICITY SERVICES FOR THE FUTURE DISTRIBUTION GRID

A Thesis

by

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ABSTRACT

The Distribution Grid across the world has been undergoing profound changes over the past decade. In developed nations, electrification of the transportation sector and integration of Distributed Energy Resources (DERs) has finally gained momentum. In emerging markets, electrification of rural areas brings to light the question of whether a 'centralized bulk transmission' based solution would be the best fit. These ideas have only come under consideration primarily due to great strides in technological advancement coupled with the reduction in costs of such technologies. However, this massive transformation in the physical and technological aspects of the grid could directly conflict with existing business models and pricing strategies applied to the customers.

The main objective of this work is to propose a system where the implementation of these grid-edge technologies is in the interest of all parties involved in the energy ecosystem - utilities, retail energy providers, and the end-users. This proposed restructure of the utility business model is based on a shift in philosophy, from treating electricity as a *commodity* where the users are charged based on their volumetric consumption, to treating it as a *service* provided to the end-user by the utility company for a *fixed customer-specific Grid Access Fee*. It is designed for a deregulated wholesale and retail electricity market setting, like in Texas. This mechanism calculates the 'impact' of a customer on the distribution grid by evaluating the customer on metrics that contribute directly to the costs incurred by the utility companies.

Upon testing the new rate calculation mechanism against the old, it is observed that the distribution of bills for end-users is less centered around the mean, indicating that there are a few 'heavy-weight' customers who cause the most impact to the grid, and some of the 'light-weight' customers are overpaying in the existing scheme. Under the new scheme, the impact of customers on the grid is now more directly linked to the bill of that customer,

thus aligning the customer's incentives with that of the utility. The potential for additional human-centered grid services has also been illustrated.

DEDICATION

To my grandparents, for injecting positivity and magic,

To my parents, for supporting me even in times tragic,

To Jam, you transcend the realm of mere words and logic.

ACKNOWLEDGMENTS

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Contributors

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All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

DER	Distributed Energy Resource
IoT	Internet of Things
REP	Retail Energy Provider
TDU	Transmission Delivery Utility
EV	Electric Vehicle
PV	Photo Voltaic Cell
kWh	kilo Watt hour
kW	kilo Watt
BTM	Behind-The-Meter
GW	Giga Watt
US	United States
NSF	National Science Foundation
LRAM	Lost Revenue Adjustment Mechanism
ROI	Return on Investment
W	Demand Magnitude Impact Factor
V	Demand Variability Impact Factor
μ	Peak Demand Indicator Function
λ	Peak Variability Indicator Function
$\S^t$	Total System Demand at time t
β^t	Total System Variability at time t
S_{PeakTh}	System Demand Peak Threshold
β_{PeakTh}	System Variability Peak Threshold

X_i^t	Demand of user i at time t
dX_i^t	Variability of user i at time t
Π_W	Allocation Percentage of total target revenue for W
Π_V	Allocation Percentage of total target revenue for V

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1. INTRODUCTION

1.1 The Grid Edge Revolution

The Grid Edge can be defined as technologies, solutions, and business models advancing the transition towards a **decentralized**, **distributed**, and **transactive** grid. [1]

The Grid-Edge and DER Revolution is not just a prediction; this is happening right under our noses. Behind-The-Meter (BTM) Technologies are touted to make up over 50% of the US Market by 2021, with energy storage estimated to hit 2 GW by then [2]. Despite the fact that end-use demand is projected to increase in the next few decades both in the residential and commercial levels, there is a significant projected reduction in energy intensity [3]. This, coupled with the rise of demand-side power generation through rooftop solar PV and other DERs, implies that large-scale investments in bulk power generation units and transmission infrastructure will be significantly lower than in the past few decades.

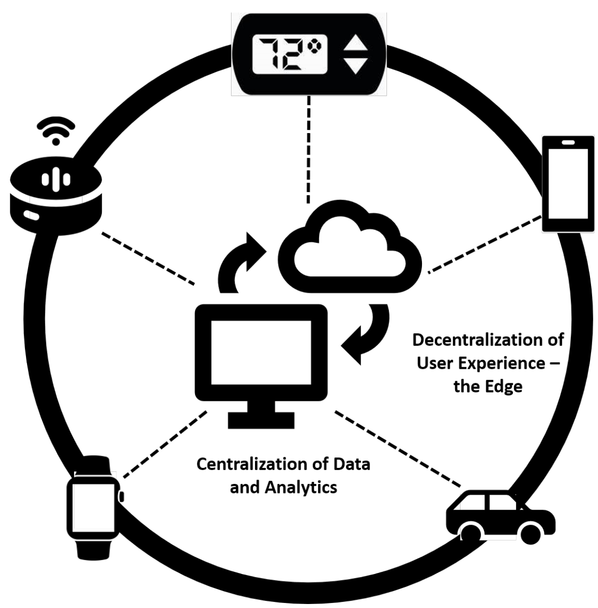

Figure 1.1: The Effect of EV Penetration in the Distribution Grid

The figure represents the market's trend towards how technology and innovation is happening more at the edge, i.e. the user-end, rather than at the centralized level, whereas analytics is centralized, with the rise of cloud-based services.

1.1.1 Major Drivers for the Grid-Edge Revolution

The key contributors to the rise of the grid edge are:

1. The rise of the *prosumer* [4]
2. New Technologies at the Customer End (IoT)
3. Electrification of the Transportation Industry (EVs)
4. Generation at the Customer End (DERs)
5. Cost-competitive storage at the customer end
6. Emphasis on the Resiliency of the Grid
7. Lack of Strong Incentives to install Transmission Lines and Bulk Power Plants

1.2 Challenges Faced by the Distribution Grid

1.2.1 Factors Contributing to Utility Expenditure

Spending on electricity distribution systems by major US Utilities has risen from $31 billion to $51 billion annually [3]. This has been largely driven by capital investment. Operations and maintenance expenses have also increased as electric distribution systems experience stress from several factors, including more customers and variable generation. The increasing amounts of customer-sited variable generation increases wear & tear on the distribution equipment required to maintain voltage and frequency within acceptable limits and to manage excessive heating of transformers during reverse power flow.

The key drivers for utility expenditure are [5]:

1. The total number of customers served

2. Customer Demand Curve
3. System Peak Load
4. Infrastructure Capital Investment & Maintenance Costs (Transformers, lines, protection & Switchgear)

1.2.2 Effect of Electric Vehicles

With increasing penetration of electric vehicles year by year, there is a critical need for distribution grid reinforcement, with additional system capacity installation seeming inevitable [6].

The figure depicts a sample distribution system on which the effect of EV Penetration has been simulated. In the distribution level, the charging infrastructure seems to be a massive contributor to a marked increase in system capacity requirements. This figure was created using Level-II Charging data profiles for 200 homes. [7]

If these charging profiles are uncoordinated, the distribution grid becomes overloaded at an EV penetration level as low as 30%. This is cause for serious concern, because to continue reliable supply of power, distribution utilities will incur heavy capital investment costs to raise the maximum system capacity limit. The costs trickle down to the customers, and that is undesirable, because not all customers are contributing to this increase in demand.

1.2.3 Effect of Solar PVs

As the penetration of Solar PV increases, distribution utilities are finding it extremely difficult to cope, due to the inherent unpredictability and intermittency of solar PV generation. The duck curve has truly impacted the grid in the sense that sudden ramping of power demand from the grid as the sun goes down creates a need for 'dirty' power plants, while also causing severe stress to the transmission and distribution infrastructure, thereby reducing the lifetimes of the equipment. With all these detrimental effects, the true killer is the fact that such customers who own Solar PV panels end up paying a significantly less monthly bill compared to the regular customer who does not cause such impacts on the grid,

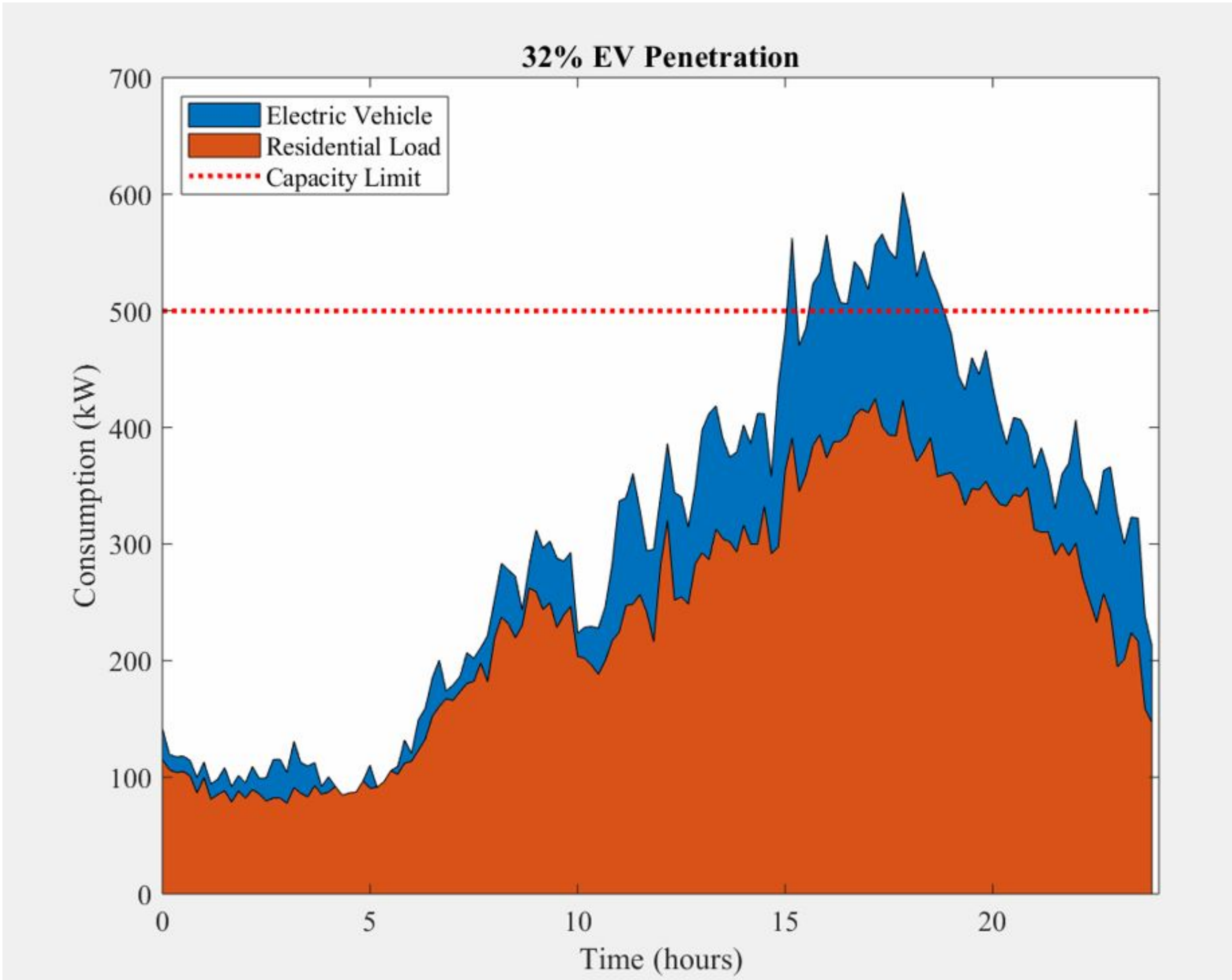

Figure 1.2: The Effect of EV Penetration in the Distribution Grid

due to flawed schemes such as net-metering [8], or by virtue of the fact that the customer demands a net total less power from the grid [9].

1.3 Human-Centered Electricity Services

When the term human factors is used in the context of engineering, it is generally considered as the application of knowledge and principles concerning human physiology and psychology to the design of specific hardware and software systems or components. In the arena of energy consumption research, human factors has not usually been defined in this way, but instead in a broader conception of the human dimensions of energy use. Researchers in the past [10] have identified seven domains of human factors in energy analysis:

(1) variability of behavior and energy use, (2) public opinion and attitudes, (3) effects of information and financial incentives, (4) social aspects of pricing, (5) energy use as a social process, (6) microbehavior in consumption environments, and (7) macro-social patterning of consumption.

In this work, the major themes focus on (1), (6) and (7), and the potential for (3) is also illustrated.

1.3.1 Participation in the NSF I-Corps

As part of a National Science Foundation workshop "NSF I-Corps" [11], I was part of a team that explored the commercial market potential of a Human-Centered Electricity Services startup, *GridGuru*[1]. Through the experience of the NSF I-Corps, I had the opportunity to interact with a wide spectrum of people, right from system operators, utility companies, retail energy providers, regulators, and several end-users, gaining insight about the problems faced by each of these members of the energy ecosystem, and what could potentially solve these. This thesis is based on some of these learnings.

1.4 Previous Work on Utility Business Models

With sea change in the utility industry, Several studies have been conducted to examine the effect of regulatory, technological, economic, and other aspects of high DER penetration in the future of the distribution grid. [12] and [13] explore the regulatory framework in different parts of the world, and the restructuring that may be required to enable an accelerated transformation towards grid modernization, while [14] argues that the existing regulatory measures may be adequate to accommodate even a transformed future. Technological innovations and Behind-the-Meter technologies have had a transformational effect in the utility industry. The resulting need for utilities to revolutionize their business practices, and a rebalancing of costs on the electricity value chain from the grid side to behind the meter have been discussed in [15] and [16] respectively.

[1]GridGuru is a residential electric plan selection and demand response platform

[17] is one of the most important and comprehensive works on reviewing the various types of business models that utilities can adopt. In [18], a Distribution Network Use-of-System (DNUoS) charge has been proposed, which aids in accurate recovery of distribution utility costs, by capturing the contribution of each user on the network to the system's costs. This idea of billing network members for their contribution to system costs has been applied in this thesis.

2.1 The Deregulated Electricity Market

In the context of this work, a deregulated electricity market structure has been considered [19]. In this structure, there are two transactions - the physical transaction, representing the flow of electrons (electric power), and the financial transaction, representing the flow of money.

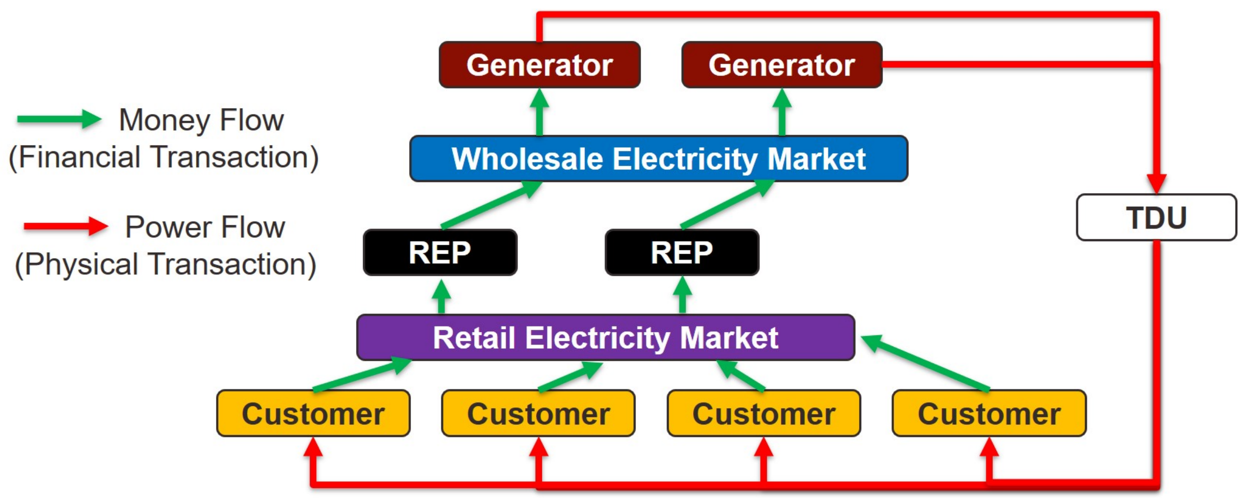

Figure 2.1: The Deregulated Electricity Market Structure

Our primary focus in this work is the Physical transaction, i.e. the flow of power from generation units to the customers through the transmission and distribution infrastructure owned by the Transmission and Distribution Utility (TDU).

2.2 Understanding the Customer's Bill

As an illustrative example, let us consider a sample electricity plan provided by Reliant Energy [20]. The electric bill for customers is divided into two categories:

1. **TDU Delivery Charges** - The objective of this fee is to recover the operation &

maintenance costs, and the capital investments made by the utilities to upgrade or expand their infrastructure.

2. **Energy Charges** - charged by the Retail Energy Provider. This essentially exists to recover the costs incurred by the generator and the Retail Energy Providers.

Electricity Facts Label
Reliant Energy Retail Services, LLC
Reliant Power On 15 plan
CenterPoint Energy service area
Date: 03/01/2019

Electricity price

Average monthly use:	500 kWh	1000 kWh	2000 kWh
Average price per kWh:	11.4¢	10.4¢	9.8¢

This price disclosure is based on the following components:

Base Charge:	$5.00	per month
Energy Charge:	5.6388¢	per kWh
CenterPoint Energy Delivery Charges:	$5.47 per month and 3.6876¢ per kWh	

CenterPoint Energy Delivery Charges include all recurring charges passed through without mark-up. This price disclosure is an example based on average prices - your average price for electricity service will vary according to your usage. The price you pay each month will consist of the Base Charge, Energy Charge, and CenterPoint Energy Delivery Charges.

Figure 2.2: A Sample Electricity Facts Label

Let us take a closer look at the TDU Charges.

The existing TDU Charges are fashioned as a combination of a small fixed charge, coupled with a larger volumetric ¢/kWh charge. Thus, the customer's TDU Charges increase with an increase in total power consumed by that customer from the grid. This volumetric charge could be flat, vary based on consumption thresholds (tiered pricing), or have varied rates based on time of consumption. The relative distribution of the fixed part vs volumetric part varies by region and from customer to customer, but the current scenario largely features the fixed charges accounting for a significantly less percentage of the total bill than volumetric charges. The TDU Charges are akin to a toll fee for using the TDUs grid infrastructure.

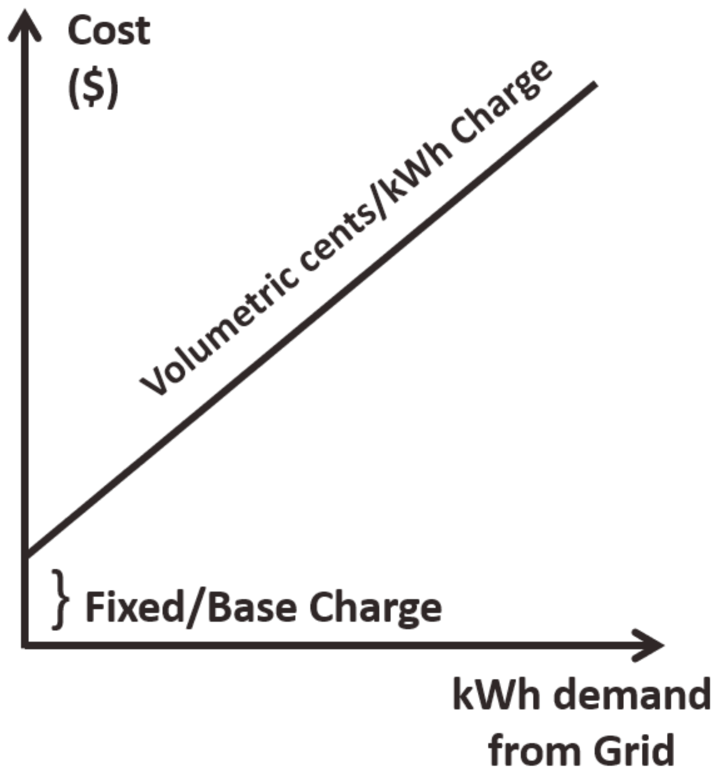

Figure 2.3: Typical Utility Bill Cost Curve - More the Volumetric Throughput, Higher the Utility Revenue

2.3 The Volumetric Throughput Incentive of Utility Companies

With the present scenario of a small fixed charge coupled with a larger variable charge based on volumetric kWh consumption, it seems clear that the revenue earned by utilities is directly proportional to the volume of electricity in kWh that flows through their distribution network. This clearly incentivizes utilities to maximize sales and try having more power flow through their distribution network. In this manner, the utilities can increase their revenues, thus recovering their costs and maximizing their profits. This is detrimental to the aforementioned objective of grid modernization: to make the grid more clean, reliable, resilient, and efficient.

The Grid Edge Revolution thus poses a severe threat to utility companies that continue to operate under the older outdated business practices in the modern day. As discussed earlier, Solar PV penetration directly results in reduction of kWh demand from the grid-center, thus reducing the customer's utility bill, even though the utility company offers the service of access to the grid at all times, without which the customer will not survive when the sun goes down.

The utility company has several responsibilities that need to be met to ensure the customers' lights remain turned on - operation & maintenance of devices, system planning & scheduling, and most importantly ensuring that the transmission and distribution network has enough capacity to actually deliver the power from the generators to the customers.

2.4 Desirable Characteristics of the New Rate Structure

1. Must Capture the true causes of costs for distribution utilities

2. Equitable Allocation of Costs to each customer

3. Rigorous methodology (Precise, Data-Driven)

4. Simple for the Customer

2.5 Eliminating the Conflict of Interest

There is thus a dire need to restructure the utility business model, so as to better align with the aforementioned objectives of a Grid Edge Future.

Essentially, the distribution utility needs to find alternate approaches to recover their fixed costs [21]. Some key ideas touted to achieve these objectives include - increase in fixed charges, introduction of minimum bills, demand charges, revenue decoupling, time-varying rates, tiered pricing, or lost revenue adjustment mechanisms (LRAMs).

It seems clear that an increase in fixed charges levied on customers would be a much better way to assure utilities of a certain level of revenue without the detrimental effect of the throughput incentive. However, this raises the concern that with lower volumetric charges, consumers would lose their incentive to minimize their usage; furthermore, their prior investments into usage minimization & energy efficiency, including star-rated appliances and even rooftop solar PV would now have a much longer payback/ROI period. Another key issue about increased fixed charges across all customers is the lack of equitable collection from all users - the policy would disproportionately impact low-usage consumers.

The goal here is now to design a rate such that it captures the true cost incurred by the distribution utility to service a certain customer. Essentially, the rate must be reflective of the customer's actual *impact* on the grid.

Following this, a new TDU Rate Calculation Mechanism has been proposed. Let us look into this in more detail.

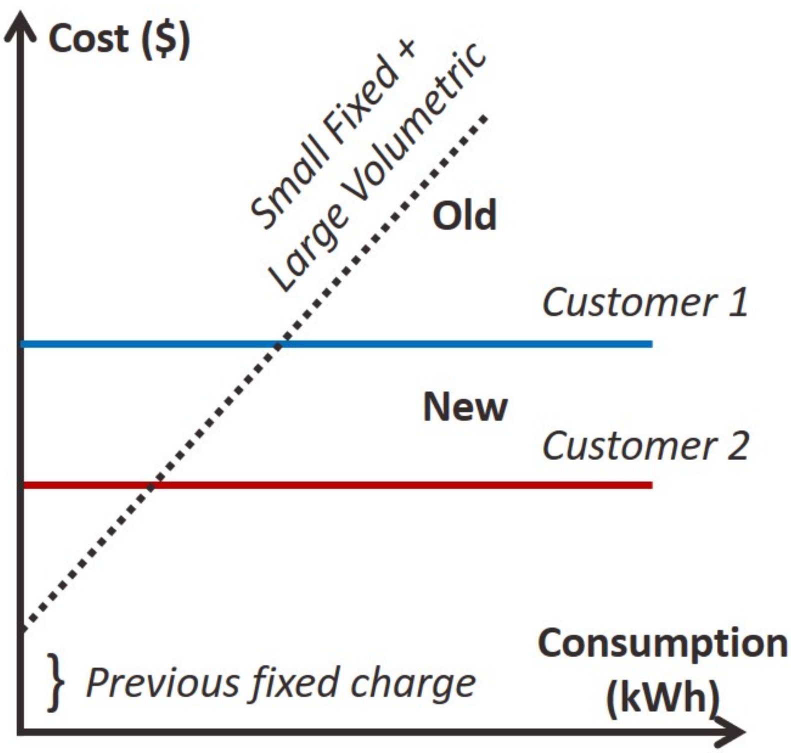

Figure 3.1: Old vs. New TDU Charges : Cost Curve
Cost ($) vs Consumption (kWh)

The new TDU Charge features the introduction of a fixed grid-access fee, which would completely replace the traditional small fixed + large volumetric structuring of utility pricing. The unique flavor of this idea lies in how these grid-access fees would be customer-specific, calculated for each customer by taking into account some key parameters that define the impact of said customer on the grid. This impact is quantified through a combination of weighting factors called Grid Impact Factors.

This concept is analogous to that of an insurance rates model or a credit score, where each customers rates/credit limit are appropriately scaled to accurately reflect the risk level taken up by the insurance company / bank by entering into business with said customer.

3.1 Shapley Value

The Shapley Value is a means of evaluating a game, by measuring the value of each player in the game. [22] It is a solution concept in cooperative game theory, where to each cooperative game it assigns a unique distribution (among the players) corresponding to their respective contribution to the overall value of the group.

3.1.1 Formal Definition

Coalitional Game: There is a set N (of n players) and a function ν, such that $\nu : 2^N \to R$ with $\nu(\emptyset) = 0$, where $\emptyset$ denotes the empty set. ν is called a characteristic function, with the following meaning: if S is a coalition of players, then *v(S)*, called the worth of coalition S, describes the total expected sum of payoffs the members of **S** can obtain by cooperation.

The Shapley Value is one way to distribute the total gains to the players. It has several desirable properties (listed below), making it a "fair" distribution.

The Shapley value (ϕ_i) for network i is obtained by:

$$\frac{1}{N!} \sum_{\pi \in \Pi} (\nu(S(\pi, i) - \nu(S(\pi, i) \setminus i))$$

where ν is the cost function, Π is the set of all possible permutations of players N and $S(\pi, i)$ is the set of all players in ordering π without i and including i.

3.1.2 Properties of Shapley Value

1. **Symmetry or Equal Treatment:** If two players in a game are substitutes (i.e. the worth of no coalition changes when replacing one of the two players by the other one), then their values are equal.

2. **Null or Dummy Player:** If a player in a game is such that the worth of a coalition

never changes when he joins it, then his value is zero.

3. **Efficiency or Pareto Optimality:** The sum of the values of all players equals $\nu(N)$, the worth of the grand coalition of all players (in a superadditive game $\nu(N)$ is the maximal amount that the players can jointly get; this property actually combines *feasibility* with *efficiency*).

4. **Additivity:** The value of the sum of two games is the sum of the values of the two games

These properties uniquely determine one payoff vector for each game. The Shapley value of a player i in a game v turns out to be exactly the *expected marginal contribution of player i to a random coalition S*.

3.2 Shapley Value Approximation for Calculating Impact on the Grid Due to each Home i

The approach of applying a Shapley Value Approximation to calculate Grid Impact Factors is analogous to the methodology followed in [23], which dealt with bill calculation schemes for Internet Traffic.

In the context of a Distribution Grid, the Installed Capacity of the system is a key parameter - it determines how much load can be served to the customers, and depending on changing load patterns, this limit also dictates the need for capital investment. System Capacity requirements are directly dependent on the System Peak Demand to be supplied to the customers at any given time t. Thus, the "Peak Demand Time Slots" are a critical time for the system. Thus, a Demand Magnitude Impact Factor W is introduced, that measures the demand impact weight of each home during the peak demand time slots.

$$\text{Demand Impact Weight of Home } i\ (W_i) = \text{Total Demand of Home } i \text{ during Peak Slots}$$

Another key concern for the distribution grid is the health of the existing infrastructure. This directly impacts the capital investment and maintenance costs that the utility incurs. The health of grid infrastructure is correlated to its loading conditions and the fluctuations in demand. These fluctuations are measured in the Demand Variability Impact Factor V, during the peak variability time slots of each home.

$$\text{Variability Impact Weight of Home } i\ (V_i) = \text{Total Variability of Home } i \text{ during Peak Slots}$$

Following these, the allocated costs for each home are given as follows:

$$\text{Cost Allocation of Home } i = \frac{\text{Impact Weight of Home } i}{\text{Sum of Weights for all Homes}}$$

As is evident from the figure, the utility company in the past did not have their revenue under their control, i.e. they would have to watch and hope that consumers use more kWh, thus driving up their revenue. But now, the utility has a steady and assured income from each consumer via the fixed Grid Access Fees. In the figure, Customer 2 has a lower impact than Customer 1, and thus is charged a lower Grid Access Fee.

3.3 Peak Indicator Functions

With the objective of making the rate structure as flexible and general as possible, the idea of Peak Indicator Functions for Demand and Variability has been introduced. These take as inputs the present system conditions, the peak threshold for the system conditions, and a strictness parameter k, to deliver an output of an indication whether the system condition at that time t is considered to be a peak slot or not. When k is very small, the Peak Threshold is considered a very strict cut-off, whereas if k is larger, the function also begins to consider those time slots where S^t is almost equal to the peak threshold, thus reducing the importance and emphasis placed on an inherently arbitrary definition of peak threshold.

Peak Indicator Functions have been defined for Peak Demand Magnitude (S) and Peak Demand Variability (β) as μ and λ respectively. These are described below.

3.3.1 Peak Demand Magnitude Indicator μ

This function is designed similar to a logistic function, and is centered around the System Peak Threshold value S_{PeakTh}. S_{PeakTh} is calculated based on a percentile value that can be set by the distribution grid operator. If the peak threshold percentage is set as 15%, then $S_{\text{PeakTh}} = 85^{th}$ percentile of System curve S. This means that a given time slot t is defined as a peak demand time slot when $S^t \geq S_{\text{PeakTh}}$. In essence, this function returns 1 if it is a peak slot, and 0 if not. For a given time t, μ is described as follows:

$$\mu^t = \frac{1}{1 + e^{\frac{-(S^t - S_{\text{PeakTh}})}{k}}}$$

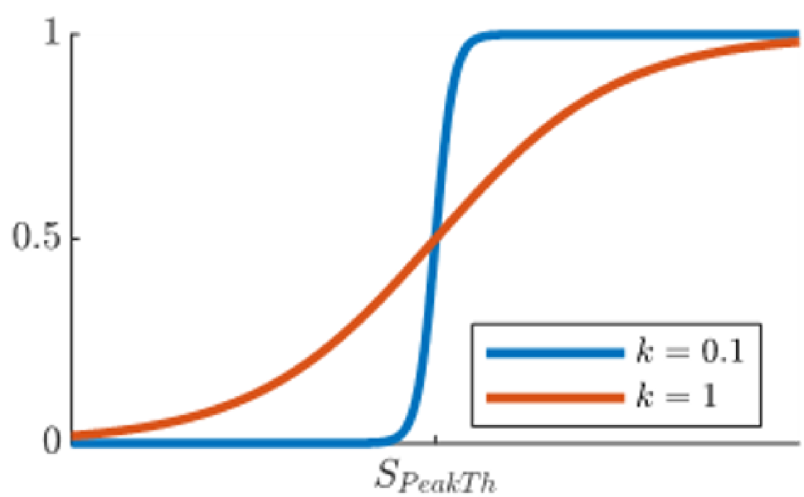

Figure 3.2: Peak Demand Magnitude Indicator Function μ

3.3.2 Peak Demand Variability Indicator λ

The Variability indicator has the additional unique property of not only indicating that a given slot is a peak slot, but also capturing how big the peak is.

Similar to S_{PeakTh}, β_{PeakTh} is calculated based on a percentile value that can be set by the distribution grid operator. A given time slot t is defined as a peak variability time slot when $\beta^t \geq \beta_{\text{PeakTh}}$. For a given time t, λ is defined as follows:

$$\lambda^t = k \ln(1 + e^{\frac{(\beta^t - \beta_{\text{PeakTh}})}{k}})$$

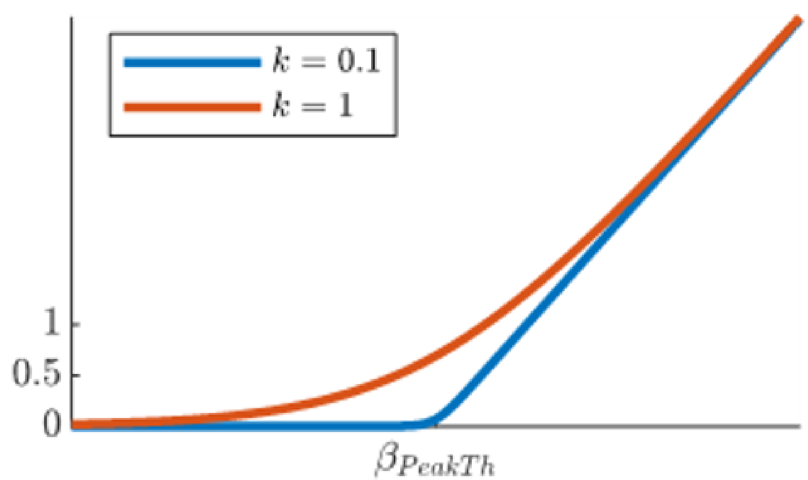

Figure 3.3: Peak Demand Variability Indicator Function λ

3.4 Calculating the Grid Impact Factors W and V

Let X_i^t = Demand of user i at time t

dX_i^t = Change in Demand of user i between time t and $t-1$

i.e. $dX_i^t = X_i^t - X_i^{t-1}$

3.4.1 Element-Wise Multiplication

$$W_i^t = X_i^t \cdot \mu^t \qquad V_i^t = dX_i^t \cdot \lambda^t$$

$$W_i^t = \sum_t W_i^t \qquad V_i^t = \sum_t V_i^t$$

3.4.2 Matrix Multiplication

$$W_{N\times 1} = X_{N\times T} \cdot \mu_{T\times 1} \qquad V_{N\times 1} = dX_{N\times (T-1)} \cdot \lambda_{(T-1)\times 1}$$

$$N \text{ homes}, T \text{ timesteps} \qquad N \text{ homes}, (T-1) \text{ time differences}$$

3.4.3 Relative Weight (% Allocation) for each Home i

$$W_{\text{share } i} = \frac{W_i}{\sum_{j=1}^{N} W_j} \qquad V_{\text{share } i} = \frac{V_i}{\sum_{j=1}^{N} V_j}$$

3.5 Calculating the Final Bills

Let $B_{i\text{ total}}^{\text{old}} \to$ Total Bill of home i calculated in the old method,

and $B_{i\text{ total}}^{\text{new}} \to$ Total Bill of home i calculated in the new method.

The data used is for a period of 2 years, i.e. 24 months. To calculate bills for each home under the old mechanism, we consider a standard rate formula for TDU Charges defined as follows:

$$B_{i\text{ total}}^{\text{old}} = \sum_{\text{mo}=1}^{24} (\$5 + 0.05 \times \text{kWh}_i^{\text{mo}})$$

In the new rate calculation mechanism, customers are charged a fixed monthly bill based on their Grid Impact Factors. This fixed charge is calculated by starting from the total target revenue for the utility company. This is the reverse approach of the existing mechanism, thus a stark difference from the procedure followed in the traditional scheme, where the individual customer's rate is based on a fixed formula, and an aggregation of all customers' payments gives the total revenue for the utility company.

To make a fair comparison of both the mechanisms, the total revenue for the utility company has been fixed as the $B_{i \text{ total}}^{\text{old}}$ value, i.e.,

$$\sum_{i=1}^{N} B_{i \text{ total}}^{\text{old}} = \sum_{i=1}^{N} B_{i \text{ total}}^{\text{new}}$$

Since the new mechanism has to account for two contributing grid impact factors W and V, the importance of these respective weighting factors are determined by the allocation percentage parameters Π_V and Π_W, defined as follows:

$\Pi_W =$ % Allocation of Total Target Revenue for W

$\Pi_V =$ % Allocation of Total Target Revenue for V

And so, finally, the total bill for each home i as per the new scheme is calculated as a linear combination of the weighting factors scaled with their respective allocation percentage parameters, as follows:

$$B_{i \text{ total}}^{\text{new}} = W_{\text{share } i} \times \Pi_W + V_{\text{share } i} \times \Pi_V$$

4. EXPERIMENTAL TESTING AND RESULTS

4.1 About the Data

The data used for the subsequent results in this work is the instantaneous kW Demand for 200 residential customers, measured at a resolution of 1-minute. The dataset was obtained from Pecan Street Dataport [24], with the slice of the data used being for a period of two years (01-01-2016 to 12-31-2017).

4.2 System Demand and Variability

The first step is to assess the system demand and system variability, with those being the key metrics based on which the new rate calculation mechanism is computed. A drawback of computing S_{PeakTh} and β_{PeakTh} across all time periods is that due to the inherent seasonality of the electric power system demand patterns, the 'peak' S^t values would consider only the time slots in summer months (the typical peak consumption period in ERCOT) as "peak demand time slots". This would essentially mean that the algorithm treats consumption during other months as negligible, which is quite inaccurate. To counter this issue, the system peak functions S_{PeakTh} and β_{PeakTh} are calculated on a monthly basis, as shown in Figure 4.1 (red trace).

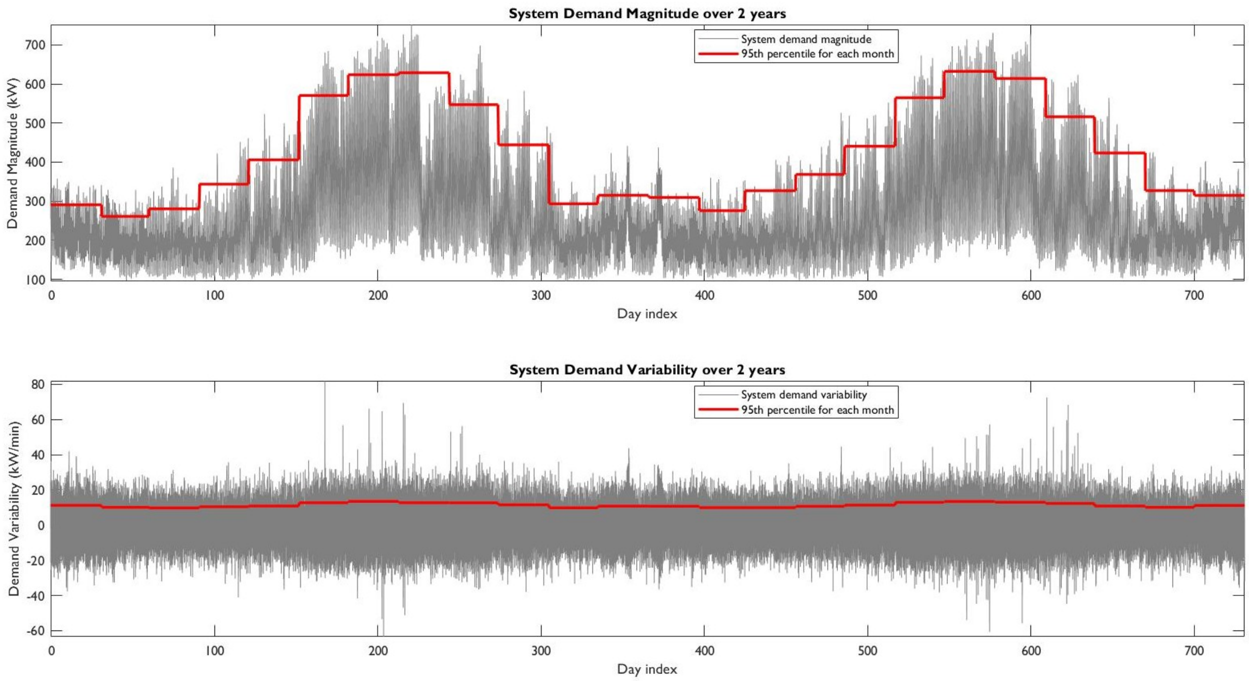

Figure 4.1: Total System Demand and Variability Curves

4.3 Percentage Change of Customer Bill due to the New Mechanism

This is a key metric based on which the performance of the new mechanism can be described. Here, the percentage change of the customer bill is defined as follows:

$$\%\text{Change of Customer Bill } = \frac{B_{i\ \text{total}}^{\text{new}} - B_{i\ \text{total}}^{\text{old}}}{B_{i\ \text{total}}^{\text{old}}} \times 100\%$$

As is evident from Figure 4.2, there are a significant number of 'winners' (negative % change $\rightarrow$ savings in the new scheme) and 'losers' (positive % change $\rightarrow$ additional expenses in the new scheme).

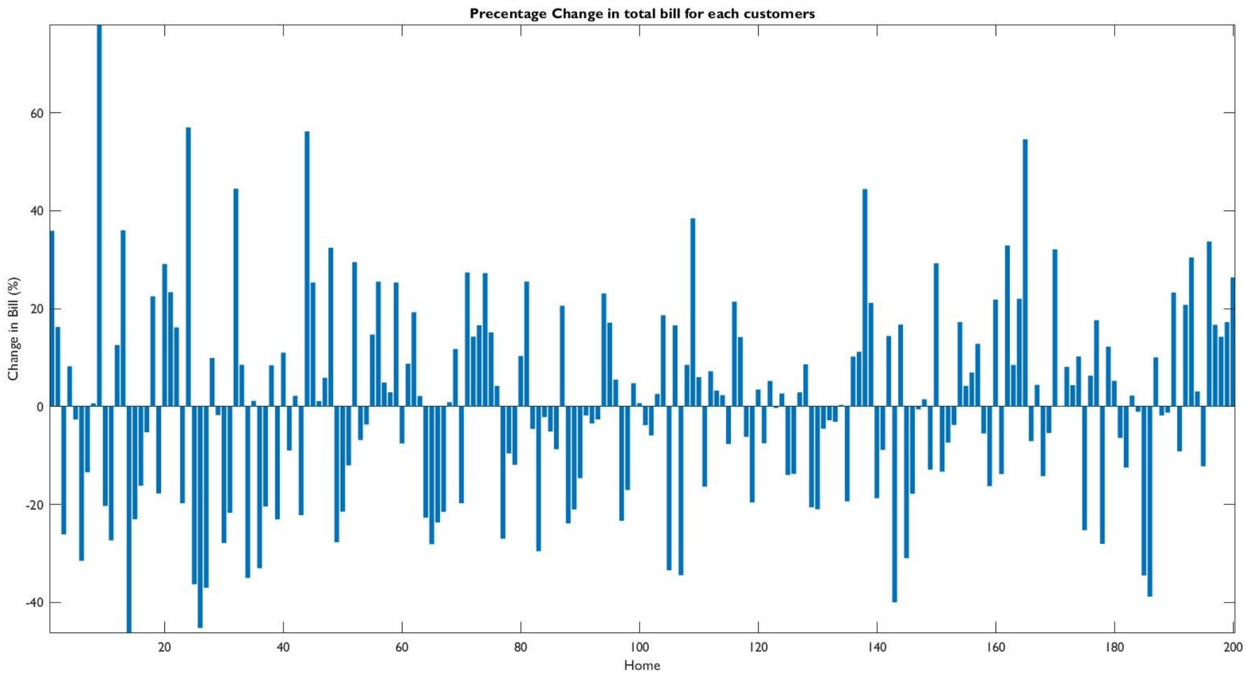

Figure 4.2: Percentage Change in Cost Allocation for each Home

4.4 Relationship between % Change and Old Bill

To check if any patterns can be identified, we explore the relationship between the change in percentage allocation of cost and the previous customer bill. In Figure 4.3, for a given value of the X-Axis, there are multiple Y-axis points falling on the spectrum of positive as well as negative. This indicates that the new bill is being computed on a totally different metric, not correlated to the old bill. Since the X-Axis refers to what the old bill was for these customers, let us examine why the bills for some are more, and others are less than the old bill, i.e. why some are 'winners' and others are 'losers. We compare two such points, that have been marked in red.

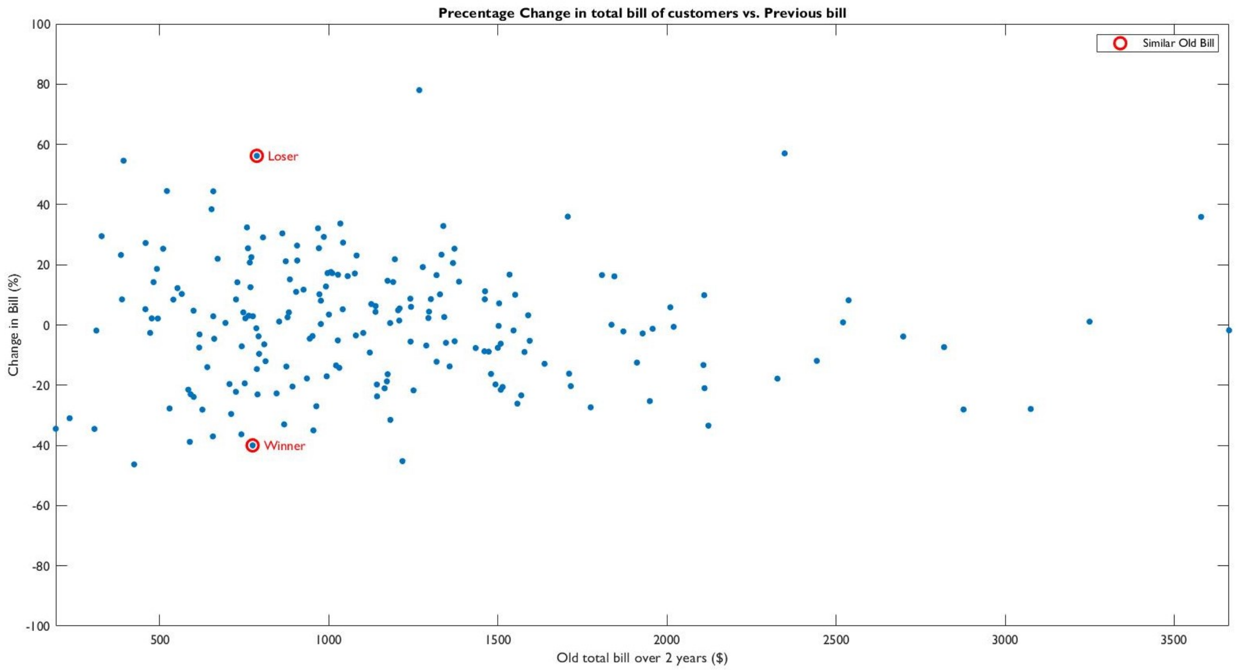

Figure 4.3: Relationship between Change in Percentage Allocation of Cost and the Previous Bill of the Customer

4.5 Winners and Losers in the New Scheme

In the Figure 4.4 (top), the system demand curve has been plotted along with the Peak Threshold line (red). This indicates what time stamps are considered as peak slots.

Figure 4.4 (bottom) depicts the demand curves of customer 1 and 2 during these peak slots. The plot shows a clear explanation as to why customer 2 (orange) was the loser and customer 1 (blue) was the winner. During the peak time slots, the demand of customer 1 far outstrips that of customer 2.

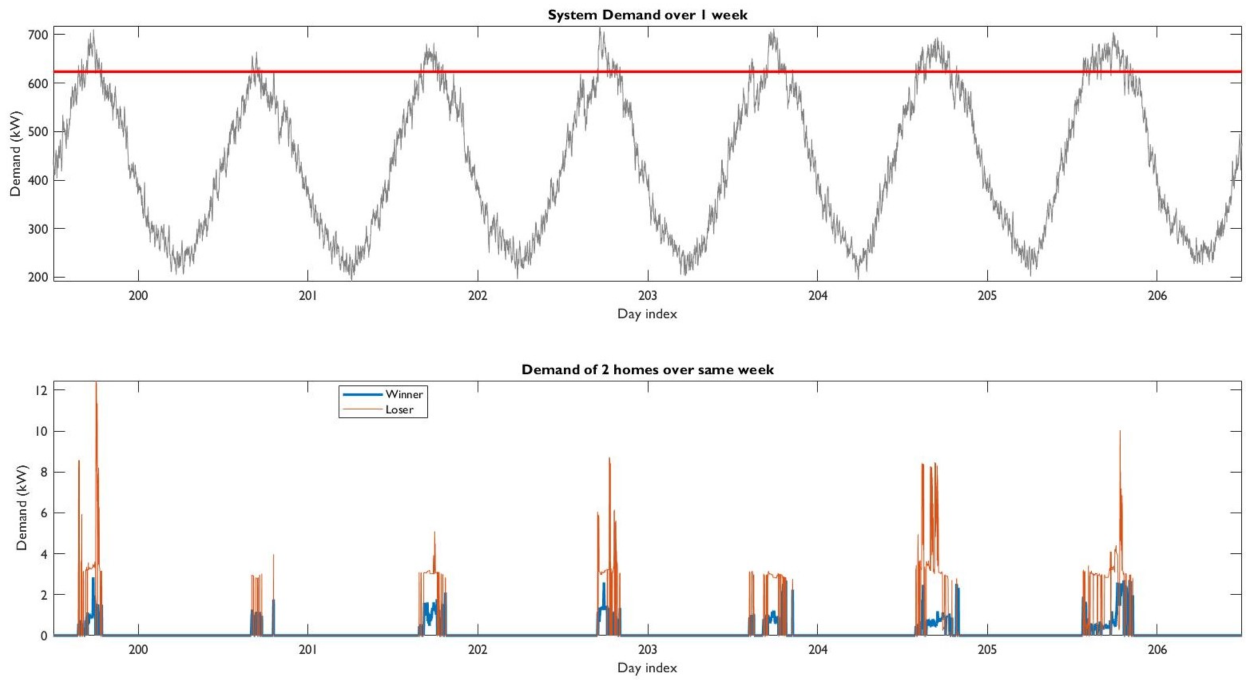

Figure 4.4: Examining Two Customers with Similar Old Bill but Different New Bill

4.6 Long-Term Characteristics: Average Demand for Each Hour

Of course, Figure 4.4 may have the propensity to be biased, running the risk of validating the underlying methodology based on a very specific data slice. Let us mitigate that risk by looking at a more general characteristics of the given data for the two customers and the same system curve. In 4.5 (bottom), we see that the peak hours of system demand are during hours 15 to 19. Comparing this to the Orange bars in 4.5 (top), which represents Customer 2, it is clear that customer 2's peaks coincide with that of the system. Customer 1 (blue) does increase a bit during the system peaks, however customer 1 is also quite well distributed, consuming perhaps similar kWh as customer 2 but during off-peak hours, like between hours 0-8. It therefore follows that customer 2 deserves to be the 'loser' based on this comparative analysis.

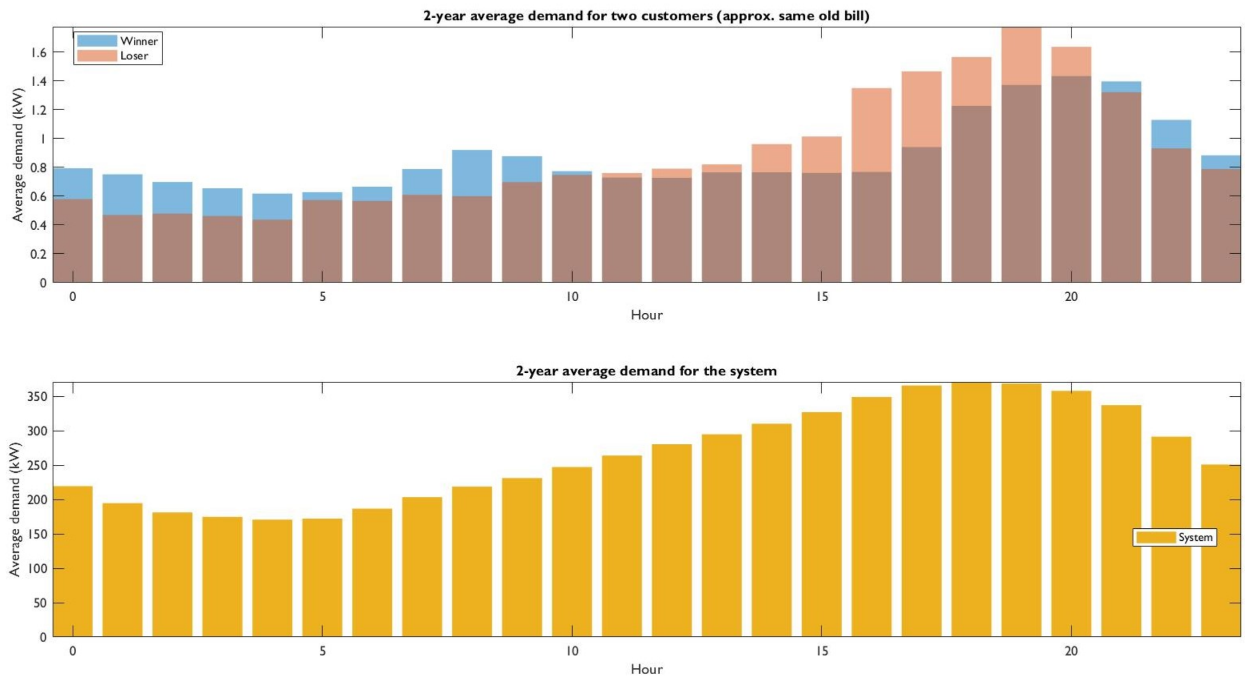

Figure 4.5: Average Demand over the Full Time Period, computed for Each Hour

4.7 Comparative Study of the Two Customers' Peak vs Non-Peak Behavior

To reinforce the previously obtained result, we take a close look at samples of the customers' data during the peak and non-peak conditions of the system. Consider the non-peak time of 5AM - 6AM (4.6). If we zoom into the usage patterns, it is noted that the orange curve is spikey (high variability) but not high magnitude for a long time. However, the blue curve (customer 1, the winner) has a certain steady demand on the grid, which is on average higher than that of the customer 2. But since this is an off-peak hour, neither customer is penalized during this time, so one can say that customer 1 gets away with consuming more.

Similarly looking at the peak hour demand profiles (4.7), we see that customer 2 far outstrips customer 1 in demand from the grid. Since this is a peak hour, the algorithm definitely takes this activity into account, and so the customer 2 is attributed a heavier weight compared to customer 1, thus ending up as the loser.

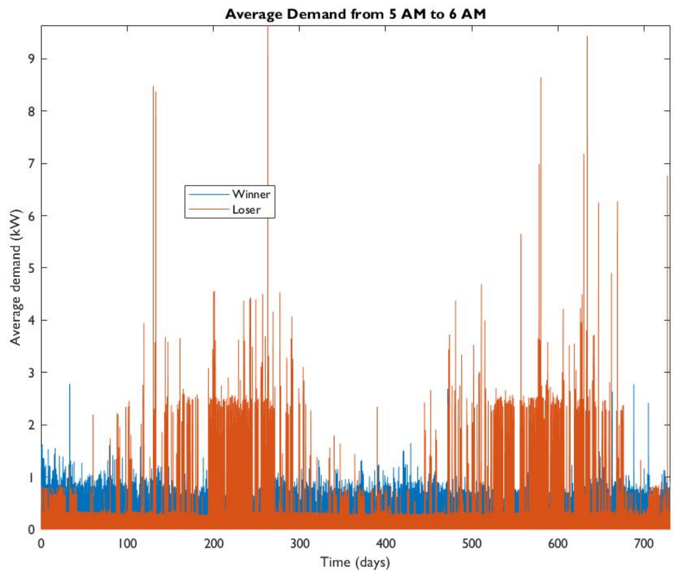

Figure 4.6: Average Demand for the Two Customers at 5AM - 6AM: Illustrates Comparative Behavior during Off-Peak System Conditions

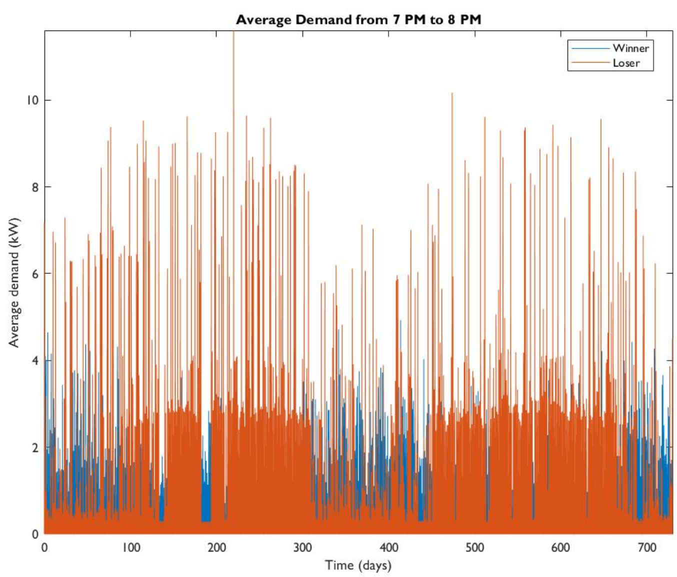

Figure 4.7: Average Demand for the Two Customers at 7PM - 8PM: Illustrates the Comparative Behavior during Peak System Conditions

4.8 Comparing the Old and New Billing Scheme for all Homes

Figures 4.8, 4.9, and 4.10 describe the effect of the new billing mechanism for each subset of homes. This effect is quantified by evaluating the difference between the old bill and the new bill, i.e. $B_{i\ \text{total}}^{\text{old}} - B_{i\ \text{total}}^{\text{new}}$ for each home. The distribution of this range has been plotted, categorized based on the type of home: EV Homes, PV Homes, and non-DER Homes.

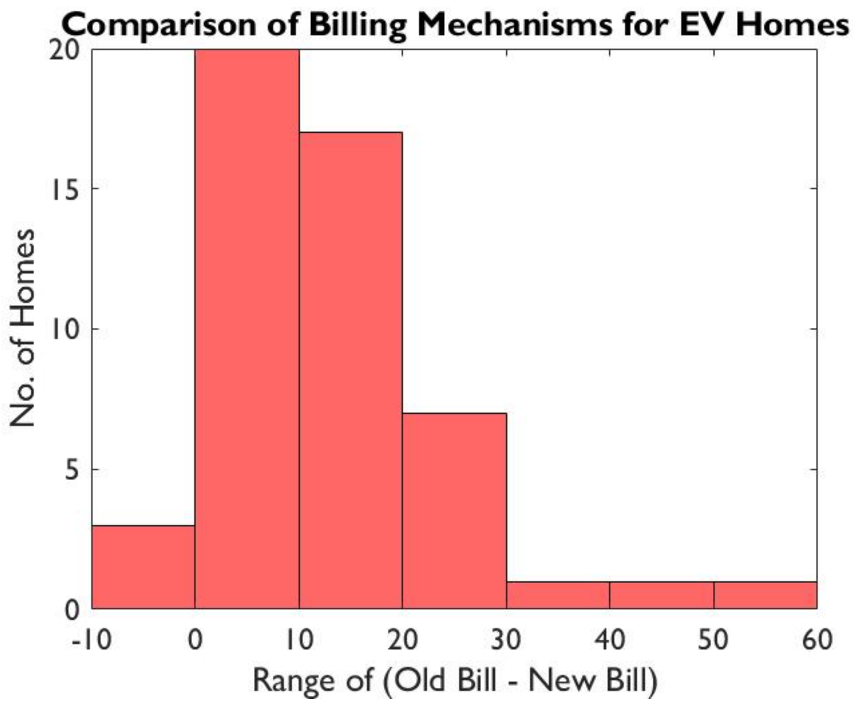

Figure 4.8: Difference between Old Bill − New Bill for Electric Vehicle Homes

4.8.1 Homes with EVs: Old vs New Billing Mechanism

In the case of EV homes, most homes have a positive value of $B_{i\ \text{total}}^{\text{old}} - B_{i\ \text{total}}^{\text{new}}$. This means that almost all homes have a lower bill in the new mechanism than they did in the old mechanism. As a result, it seems that the new billing mechanism is *favorable for EVs*. This follows intuition, because in the previous billing mechanism, all that mattered for billing was how much kWh volume was consumed by the home. Whereas in the new billing algorithm, the "impact" of the user is calculated during the critical/peak time slots of demand, where the distribution system is under the most stress. Thus, under the new billing mechanism, there is great potential of 'smart scheduling' of EV charging during the non-peak conditions of the system, which could lead to significant savings in the monthly bill of those homes. Thus, the interests of both the distribution utility and the user are aligned.

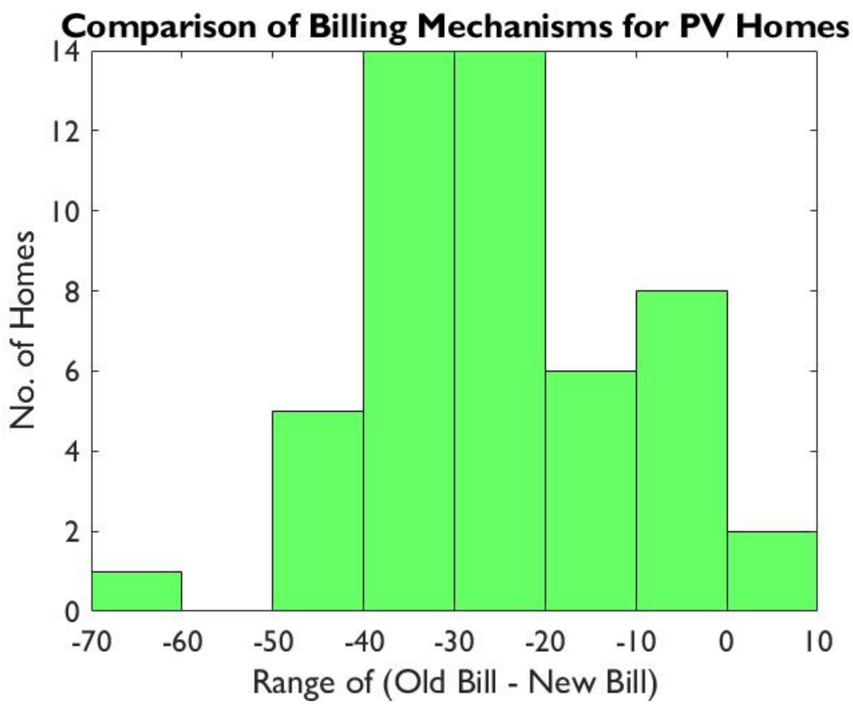

Figure 4.9: Difference between Old Bill − New Bill for Solar PV Homes

4.8.2 Homes with PVs: Old vs New Billing Mechanism

When we observe the trend for PV homes, most homes have a negative value of $B_{i\ \mathrm{total}}^{\mathrm{old}} - B_{i\ \mathrm{total}}^{\mathrm{new}}$, which means that almost all PV homes have a significant increase in their monthly bill when evaluated under the new mechanism. While this observation seems to suggest that the new mechanism is *unfavorable to PVs*, it can be argued that the new mechanism is capturing the true costs of PV that were previously (unfairly) being borne by non-PV homes. Despite the fact that the volume of consumption for PV homes is less, the sudden ramping of PV during the late evening causes significant strain on the distribution grid. This issue is captured in the new billing scheme through the Variability impact factor V.

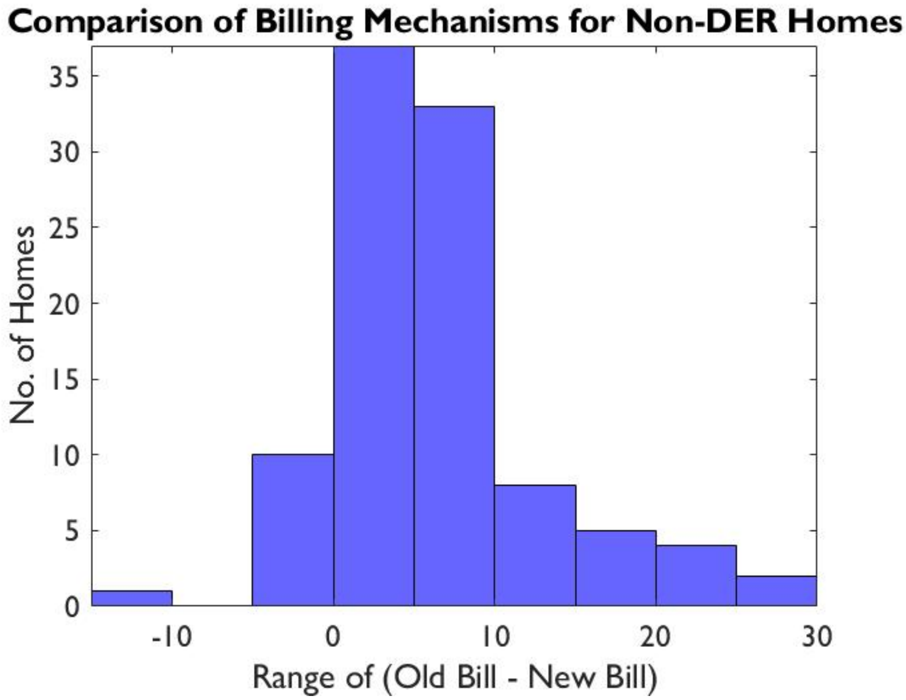

Figure 4.10: Difference between Old Bill − New Bill for Homes without DERs

4.8.3 Homes without DERs: Old vs New Billing Mechanism

Let us now consider the case of non-DER homes. Most homes have a positive $B_{i\text{ total}}^{\text{old}} - B_{i\text{ total}}^{\text{new}}$ value. More specifically, of the 100 homes, almost 90 have a positive $B_{i\text{ total}}^{\text{old}} - B_{i\text{ total}}^{\text{new}}$, with 70 homes having a slightly positive value ($0-$10 increase in monthly bill). This indicates that most non-DER homes are being benefited by the new billing mechanism. This addresses one of the key drawbacks of the previous utility billing scheme, where in many cases, costs incurred by the utilities in their PV-incentive programs such as net metering or other subsidies would be recovered from the non-PV customers. With the new mechanism, the trend of penalizing non-PV customers is reversed, bringing the distribution of bills back to balance.

4.9 Examining the effect of 25% Penetration of PV/EV on the New Billing Mechanism

Figures 4.11, 4.12, and 4.13 describe the effect of Penetration of individual DERs (EV and PV) on each subset of homes. In the default system, there is a DER penetration of 25% EV and 25% PV (50 homes each). In the system without EV, the DER penetration is 0% EV (0 homes) and 25% PV (50 homes). The first figure compares the bills of the EV Homes calculated in the default system *vs* the system without EVs. The second figure is the same, but for PV instead of EVs. The third figure shows a comparison of bills for non-DER homes calculated in the default system *vs* a system with 0% DER Penetration, i.e. no EVs or PVs.

4.9.1 EV Homes: Performance under the New Billing Scheme with and without EVs

When considering the effect of EV Penetration on EV homes, it is observed that most homes have a positive difference between with and without EV, thus following the expected trend of having higher electricity bills due to the presence of an EV. The few outliers which have a reduced electric bill despite adopting an EV can be attributed to perhaps a decrease in the variability index.

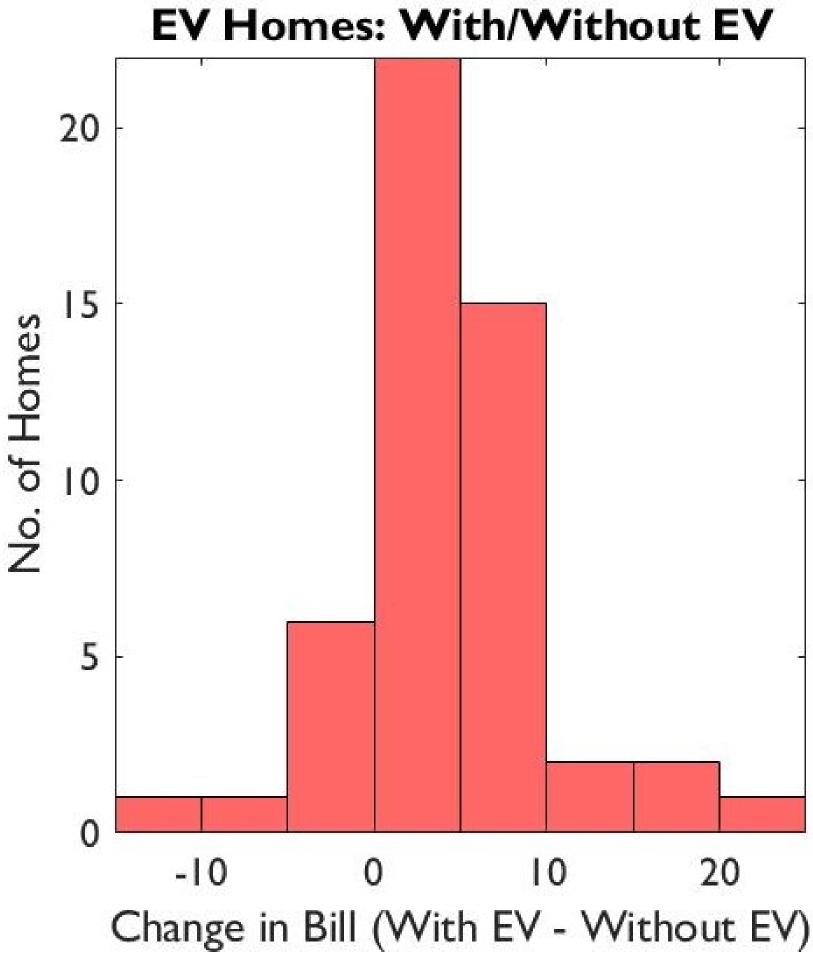

Figure 4.11: Difference of Bill for *EV Customers* under New Scheme with and without EVs

4.9.2 PV Homes: Performance under the New Billing Scheme with and without PVs

With PV however, the story is different. Some PV homes seem to benefit with the introduction of PV (around 20 homes), but the rest have a higher bill with the introduction of PV. One factor could be explained by the variability index V accounting for 25% of the total revenue, and that the PV homes have the highest variability impact factors. Another issue could be that PVs are pulling down the system conditions below peak threshold when the sun is shining, and shifting peak slots to different times.

This leads to a very interesting thought: the application of solar+storage technology

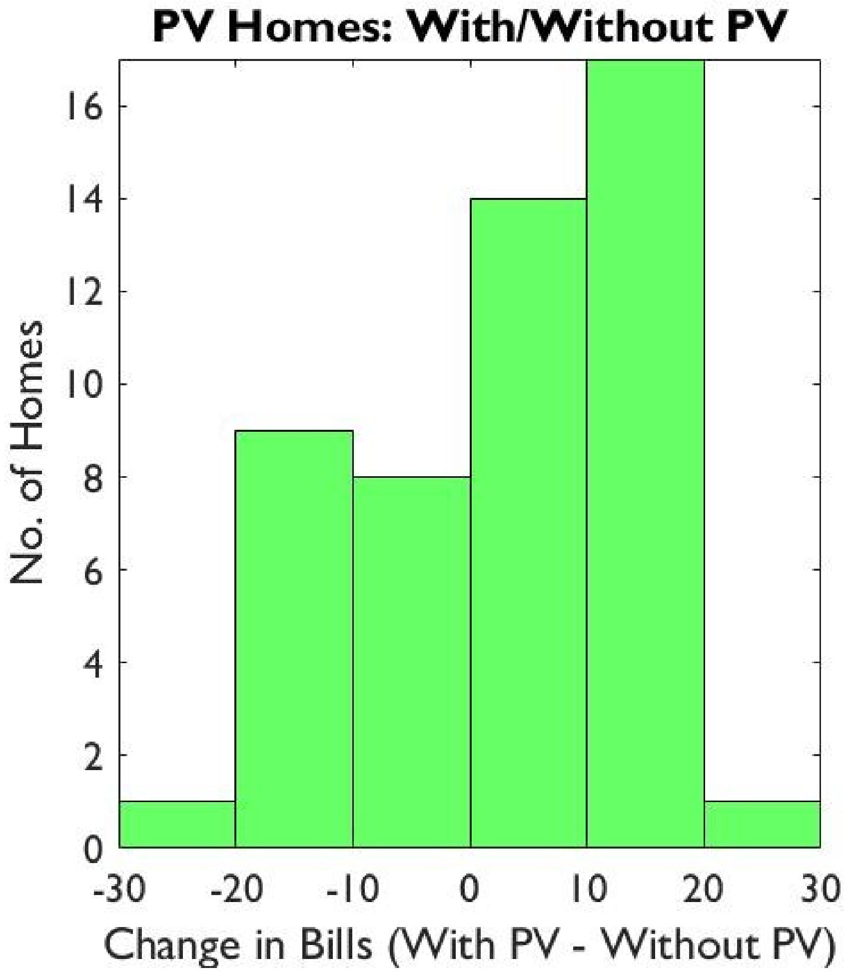

Figure 4.12: Difference of Bill for *PV Customers* under the New Scheme with and without PVs

combined with smart scheduling for maximizing usage during system non-peak conditions be the optimal strategy in the new billing scheme.

4.9.3 Non-DER Homes: Performance under the New Billing Scheme with and without any DERs

Looking at the effect of DER penetration on non-DER homes, it is noted that every single non-DER home has seen a reduction in their electric bills due to the penetration of DER. While this seems like the new mechanism is deterring people from investing in DER, it can be argued that this only occurs because PV homes are perhaps insufficiently rewarded

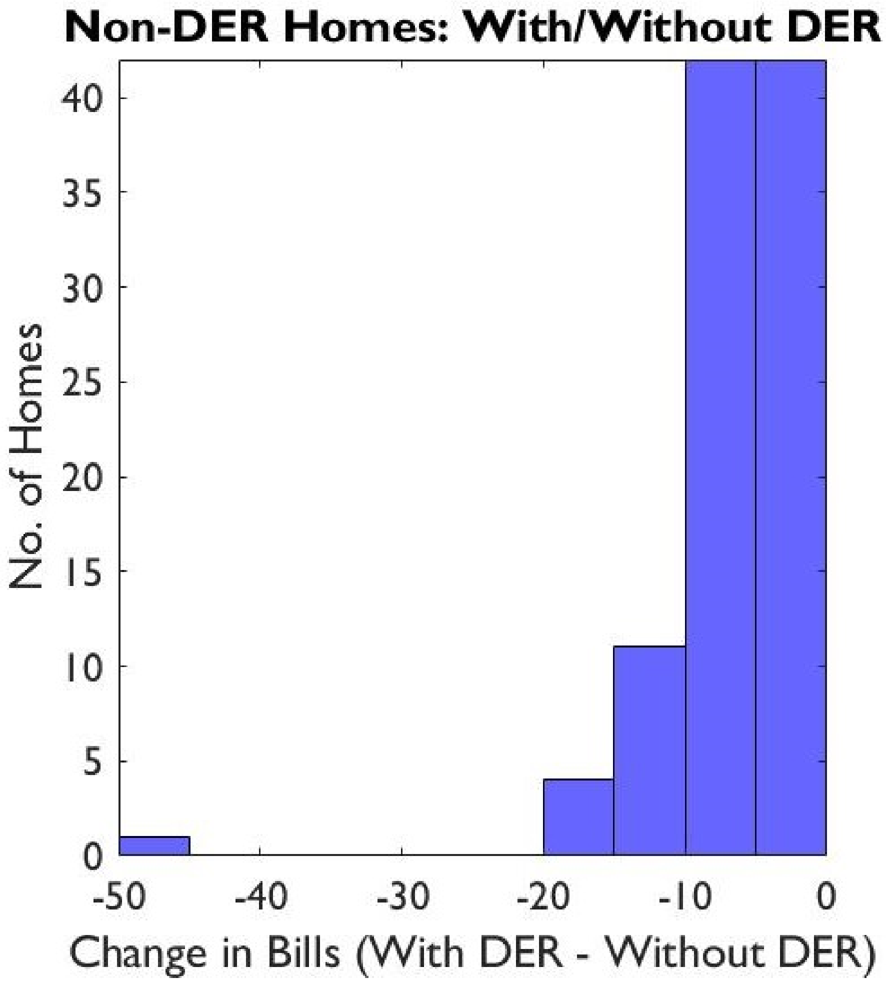

Figure 4.13: Difference of Bill for *Non-DER Customers* under the New Scheme with and without DERs

for their contribution of reducing peak system demand. Solar+storage could far outperform the existing solar-only model, thus significantly reducing the bill share of the PV homes, which in turn would cause an increased bill for the non-DER homes.

5. DISCUSSION AND CONCLUSIONS

5.1 Critical Analysis of the New Grid Impact Factor Billing Mechanism

5.1.1 Pros

5.1.1.1 Revenue Decoupling

The mechanism introduced in this work effectively decouples utility revenue and customer bills from volumetric consumption.

5.1.1.2 Recovers Utility Costs Accurately and Effectively

It is more representative of the true costs inflicted upon the distribution grid by the customers, due to the usage of kW rather than kWh as a defining metric. The introduction of 'Variability' is also a novel approach.

5.1.1.3 Utility Revenue Targets are Assured to Be Met

A very important point to note is that the new mechanism has a prominent distinction from the existing model - rather than expecting a total revenue for the utility depending on several variables, the new mechanism affords the utility the opportunity to ensure a stable and assured revenue. This is because the total target revenue is first set, and then the new mechanism allocates the costs to all customers appropriately.

5.1.1.4 Eliminates Price Risk for End-Users

On the customer end, the TDU Charges in the bill is now a fixed monthly charge, thereby eliminating price risk for customers. Also, any incentive program can now be deployed much more effectively because of the fact that the key metrics based on which the bills are calculated are much more correlated with the true causes for utility expenditure.

Thus it is clear that this mechanism offers clear benefits to both ends of the market.

5.1.2 Cons

5.1.2.1 Peak Threshold Calculation Unfair to Solar PV?

As mentioned earlier, the introduction of PV could cause the total system conditions to go below the peak threshold in some time slots, thus converting that time slot from a peak slot to a non-peak slot. However, this also shifts the peak slots to a different time, because of the fact that peak slots are defined on a *percentile* basis, rather than absolute. There will always be a top 25% set of values; it does not matter whether that range is small or large. As a result, the new system peak time slots would be those times when perhaps the sun does not shine. The appliance usage of a PV home is not offset when the sun is not shining, therefore these new shifted peak slots could be when the PV homes stop generating, and demand power from the grid, thus contributing to increase in the system demand. These slots are now the peak slots, and PV homes along with all other homes contribute to their W and V impact factors significantly during this time. Thus, it could lead to the situation where non-PV homes get away with 'bad' usage patterns when the sun is shining, because PV homes are generating enough power to reduce the stress on the system below the system peak threshold. Essentially, some non-PV homes escape penalization due to their behavior being covered or compensated for by the PV homes.

5.1.2.2 Total Target Revenue Assumption

One thing that must be kept in mind is that we are making an assumption that the new billing scheme has the same total target revenue as the old. This assumption is made to aid in comparative analysis of the two billing schemes. However, the assumption fails when applying this to a real distribution system because of the very reason why a new billing mechanism was required in the first place - the old billing mechanism does not capture the true costs incurred by the system, thus the total revenue generated using the old billing mechanism is not the best metric for the Total Target Revenue.

An issue connecting the Solar PV and Total Target Revenue is that, in case PV is introduced, the system has a lower demand when the sun is shining, thus reducing the total system stress in this period. This would result in a reduction in overall system costs, thus the total target revenue would reduce. This is not captured because of the assumption of equal total target revenue between new and old schemes.

5.2 Challenges and Opportunities

The Grid-Edge Revolution will not take place unless all stakeholders are playing for the same team. Another massive pillar of support needs to be the regulators. With regulatory policies like Performance Incentive Mechanisms rewarding/penalizing utilities for various metrics like System Efficiency, DER & Customer Engagement, Environmental Goals etc., the utilities definitely exercise much more control over their revenues, since it is now based on their own performance. This creates a win-win situation where the utility now can focus on improving and modernizing the grid infrastructure, thus enabling further penetration of DER and grid-edge capabilities into the system.

This may be quite complicated for the ordinary consumer to handle, but if the focus is to compensate all parties involved as accurately as possible while considering all the factors involved, the complicated nature of rate design comes as no surprise. Maybe this could signal the birth of a whole new industry of Grid-Edge Services; a power electronic converter offering control intelligence at the grid-edge [25], or perhaps a "Grid Guru" who could automate and manage a smart-homes energy usage according to its electric plan, while also handling peer-to-peer energy transactions within a neighborhood. With the advent of grid edge technologies and heavy penetration of EVs and DERs, the time is ripe for such ideas to come to fruition.

5.3 Summary

The primary objective of this work was to induce a philosophical shift to the way electric utility business models have been operating. This fundamental shift from treating electricity as a commodity to treating it as a **service** has been developed into a concrete rate calculation mechanism, providing an alternative to the existing business model with several advantageous features.

With the introduction of metrics such as peak thresholds and % Allocation, the utility has far greater flexibility to modify the billing mechanism as per the true costs they incur.

The previous billing scheme had some clear losers - the utility company, because their total revenue was not an assured number, as well as some non-PV users, who were being unfairly charged to finance subsidies for PV homes. With the new system, it can be argued that almost everyone is a winner, except PV users, however their fortune could be completely different if they had solar + storage.

5.4 Further Study

Future work will have to answer some key questions: the effect of solar+storage could be transformative, and thus needs to be tested. Also, further insight needs to be gained on how to calculate the actual Total Target Revenue, such that it recovers the costs incurred by utilities under different system conditions. The right method to evaluate the peak threshold remains a difficult question; multiple designs must be tested on real user data to assess which approach would most align with the objectives of this novel customer billing mechanism for efficient and accurate distribution utility cost recovery. A key area that could be explored based on this framework would be the opportunity for Value-Added Grid Services, such as Demand Response, and DER Scheduling to name a few.

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